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A PRELIMINARY INVESTIGATION OF A FLUID-FILLED ECG-TRIGGERED ANTI-G SUIT

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The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-6.

The Office of Public Affairs has reviewed this paper, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This paper has been reviewed and is approved for publication.

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This design combines the advantages of a single reservoir fluid-filled suit with external synchronized pulses of water delivered to an abdominal bladder. Such a combination has the potential of increasing perfusion to the large muscle groups of the lower extremities, decreasing blood pooling in the lower extremities and abdomen and increasing venous return to the heart. The result is reduced fatigue and improved aviator performance during sustained high $+G_z$ loads. During system assembly and testing, significant limitations in concept design and system safety were discovered. These limitations included excessive size, weight, and space requirements of the hydraulic system which prevented its use on the centrifuge. The inability to safely regulate the pulsatile fluid movement and other safety considerations barred its use in the laboratory. These safety considerations coupled with a lack of financial resources, over a prolonged period of time, to correct these technical problems forestalled further progress on this project. Work by other investigators in this area has superseded the expected benefit of this project. With continued budgetary reductions and no available in-house funding, this project must be terminated.

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EXECUTIVE SUMMARY

The fluid-filled anti-G suit has an inner and outer garment. The outer garment is constructed of a nondistensible fabric that provides resistance to water-induced distention under $+G_z$ loads. The inner garment contains a single-compartment water reservoir and a concealed abdominal bladder. The water reservoir is not in contact with the wearer. This design incorporates a separate hydraulic system which regulates the rapid pulsatile movement of fluid to the abdominal bladder. The triggering system monitors heart rate and current G-force, synchronizes the hydraulic system with the heart rate, and scales the pressure delivered to the bladder to the actual G-force. The system is responsive to all heart rates in the physiological range and to a maximal G-force of 15G.

The potential advantages of a fluid-filled ECG-triggered anti-G suit system are improved $+G_z$ tolerance. Current pneumatic anti-G suits activate with $+G_z$ loading and inflate pressure bladders over the abdomen and legs at a 1.5 psi/G rate to a maximum of 10 psi^2. The proposed system combines synchronized external pulsations with a fluid-filled anti-G suit. The system has the potential of increasing perfusion to the large muscle groups of the lower extremities, decreasing blood pooling in the abdomen and lower extremities, and increasing venous return to the heart. The result is reduced fatigue and improved aviator performance during sustained high $+G_z$ loads.

OVERVIEW AND OBJECTIVES

Current and future generations of high performance tactical aircraft will be expected to exploit the tactical advantages of sustained combat maneuvering in the 9-15 $+G_z$ environment. The current generation of anti-G suits permit aviators to operate only in the lower end of this performance envelope and only for short periods of time. Aviators are exposed to high $+G_z$ loading in order to achieve a tactical advantage; therefore, investigators must improve the anti-G suit to reduce aviator fatigue and increase aviator protection from gravity-induced loss of consciousness (G-LOC).

The proposed fluid-filled ECG-triggered device represents a combined approach. First, it reexamines the concept of water immersion. Experimental centrifuge studies of pilots immersed in water to the lower ribs, demonstrated that accelerations of up to 35G could be sustained for five seconds without visual symptoms[2]. The pressure exerted on the body surface by the water is proportional to the height of the column multiplied by the applied acceleration. Because the entire cardiovascular circulation is subjected to similar forces distributed in the same manner, the two opposing forces cancel out and the vascular transmural forces remain unchanged. In order to realize the benefit achieved by experimental subjects using immersion techniques, fluid-filled anti-G suits were investigated. Fluid must be contained in watertight fabrics that are sufficiently nondistensible to prevent suit deformity at its most weakest points. This was one of the many weaknesses of early hydrostatic anti-G suits; they lacked sufficient rigidity to prevent distention during $+G_z$ loads.

Second, the pressure exerted on the bladder is dynamically altered in response to heart rate and to G-force. While pneumatic anti-G suits vary the inflation pressure to the bladders in response to G-forces, none synchronize the inflation cycle to the heart rate. Synchronizing the inflation of the abdominal bladder to heart rate can permit increased perfusion to the lower extremities and increase venous return to the heart during sustained $+G_z$ loads that is not possible in the conventional anti-G suit. By delivering higher pressure to the bladder that exceeds central venous pressures, venous return to the heart from the abdomen will increase. Carefully regulated bladder pressure will be required to prevent abdominal aorta collapse. This careful regulation should permit continued arterial flow to the lower extremities during $+G_z$ loads. These features should allow aviators to sustain higher $+G_z$ loads at lower workloads with decreased fatigue.

INTRODUCTION AND BACKGROUND

During World War I, fighter pilots reported visual changes when pulling out of a dive or aerial combat maneuvering[1]. Investigations into the physiologic basis of "blackouts" and G-LOC date back to the 1930s when the Germans[2], United States Navy[3], and Canadian and English[4] investigators developed the human centrifuge to determine the etiology of these visual changes. In response to test results on the centrifuge, these investigators developed anti-G garments and tested them in flight or in the human centrifuge. Excellent reviews of the history of anti-G garments are available[1,2,5,6,7].

The early investigators examined a wide variety of techniques including water immersion and pneumatic and hydrostatic anti-G garments to determine optimal protection characteristics. The theoretical advantages of hydrostatic suits were unrealized due to limitations in technology and comfort. The water-containing suits were easily distensible under G-forces; they added undesirable weight; and they were uncomfortable. In Canada, Wing Commander W.F. Franks, using the newly constructed human centrifuge in Toronto, developed the Franks Flying Suit, a water-filled, double-layered rubber suit. This suit used the principle of hydrostatic counterpressure as a means of protection. The suit was combat tested by the British Royal Air Force in North Africa during World War II. The suit was rejected by pilots due to its weight and heat stress; pilots complained of a "free floating" sensation and that they could not get a feel for the aircraft's maneuvering.

Early work by Earl Wood on the human centrifuge at the Mayo Clinic demonstrated that the pneumatic anti-G garment provided superior protection over that provided by immersion in water or by the Frank Flying Suit[8]. Dr. Wood and Mayo Clinic investigators collaborated with two corset manufacturers, David Clark Company and Berger Brothers, to develop and test a pneumatic anti-G suit containing five interconnecting bladders that covered the abdomen, anterior thighs, and calves.

In Australia, Dr. F.S. Cotton of Sydney developed a pneumatic anti-G suit using the Royal Australian Air Force centrifuge to conduct his tests. This suit was successfully combat tested in the South Pacific in World War II. In 1944, the five interconnected bladder lower garment anti-G suit became standard issue to United States Army Air Force fighter pilots. Due to the limited protection, pilots typically supplemented the actions of the anti-G suit with straining maneuvers such as the L-1 or M-1 maneuvers to avoid G-LOC during high $+G_z$ loads.

In 1987, when this study was begun, a pneumatic anti-G suit, the CSU-13/BP, with a standard air control valve such as the ALAR-Hiflow was issued to fighter pilots for protection against significant $+G_z$ forces. This suit consists of a lower garment anti-G suit of nondistensible Nomex construction which had integral bladders sewn into the suit at the lower legs, anterior

thighs, and abdomen. The anti-G suit utilizes on-board air pressure to inflate the bladders. The anti-G valve opens at 2G and inflates the bladders at 1.5 psi/G to a maximum of 10 psi when relief valves open for suit and aviator protection[2].

The fact that approximately two G-LOC related mishaps per year have occurred in USAF fighter aircraft between 1982 and 1990[11] is ample testimony that the current anti-G protection systems are not enough. Improvements in the anti-G suit must be pursued.

SYSTEM DESCRIPTION

The fluid-filled anti-G suit has an inner and outer garment. The outer garment is constructed of a nondistensible fabric that provides resistance to water-induced distention under $+G_z$ loads. The inner garment contains a single compartment reservoir that can be filled with water. The inner garment reservoir provides water coverage from the thoracic inlet to the ankles. The water is displaced to dependent portions such as the lower extremities of the anti-G suit in response to $+G_z$ loading. The water reservoir does not contact the pilot.

A separate abdominal reservoir is present in the abdominal bladder. This bladder is connected to a separate hydraulic system which regulates the rapid pulsatile movement of fluid to the abdominal bladder. The triggering system used to inflate the bladder monitors heart rate and current G-force and synchronizes the frequency of the pulsed fluid delivered by the hydraulic system with the heart rate and scales the pressure delivered to the bladder to the actual G-force. The system is responsive to all heart rates in the physiological range and to a maximal G-force of 15G.

The system is divided into three parts: the anti-G suit garment, an electromechanical subsystem, and a computer subsystem. The electromechanical portion consists of the abdominal bladder, a heart rate sensor, a G-force sensor, and the pressure pumps. The computer consists of the hardware, the interfaces, and the software required to operate the system. A brief overview of the system follows.

Keyboard/Video Terminal: The user interface has the ability of continuously displaying the status of the pressure channels (enabled/disabled), the pulse rate, the current G-force, the channel waveform outputs, and pressure functions if any. The keyboard interface permits user commands. The commands run the entire system and include (run; stop; channel write; toggle channel; load, create or modify pressure arrays).

Computer and Computer Interface Board (CIB): The computer is a Zenith 248 computer which houses a CIB. The CIB contains hardware which accepts a TTL level heart beat signal and a TTL level G-force signal (4 bits representing 16 G-force levels). The

G-force signal is polled whenever a heart beat signal occurs. The maximal allowed G-force is 15G. The CIB outputs a maximum of four 0-5 volt pressure functions.

Translator Interface Module (TIM): The TIM accepts signals (1-5 volts proportional to pressure) from the CIB as a pressure wave set point and 1-5 volts from the bladder pressure transducer as a feedback signal. The TIM compares the set point and feedback signals and outputs a motion signal (pulse train) and a direction signal (fwd/rev) to the Stepper translator module.

Stepper Translator Module (STM): The STM accepts motion and direction commands from the TIM. The translator outputs signals to a 4-phase stepping motor. The STM and TIM are housed together in a cabinet along with their power supplies and a front panel operator interface. The panel display complements the CRT display and includes the following: a bladder pressure bar graph, stepper motor direction, motion indicators, manual direction and motion controls, and manual G-force selection.

Electrohydraulic Stepping Cylinder: This device consists of a fractional horsepower electric stepping motor, a 4-way rotary servo-valve, and a hydraulic cylinder (actuator). The stepping motor windings accept signals from the STM. These components are linked together in a hydromechanical closed loop. A pump provides hydraulic power to move the cylinder.

Test Rig: The vendor test rig simulates external pulses to a part of the human body such as the thigh. A pressure transmitter/interface box measures the pressure from the bladder side (outside) or the body side (center) of the test rig.

Hydraulic Power Unit: The device consists of a motor, pump, reservoir, and hydraulic fluid.

Fluid-Filled Anti-G Garment: The fluid-filled anti-G suit has the inner and outer garments previously described. The first, a nondistensible fabric outer garment that fits over the suit, contains the fluid reservoir and provides added resistance to prevent inner garment distention during $+G_z$ loads. The second is a watertight inner garment with a single compartment reservoir that covers the pilot from the thoracic inlet to the ankles. The reservoir volume varies with the size of the suit, but an average suit may contain approximately 3-5 gallons of water (a gallon of water weighs about 8 lb). The inner garment houses a concealed bladder in the abdominal area. The bladder and related plumbing may contain 1-2 additional gallons of water. This design did not incorporate bladders in the lower extremities. A separate hydraulic system regulates the rapid pulsatile movement of fluid in the abdominal bladder. The hydraulic system is activated by a triggering system which uses the "R" wave of an ECG complex to gate the pulsations to the heart rate. The pressure delivered to the bladder is dynamically variable and is scaled by the monitored G-forces.

SYSTEM DESIGN FLAWS

The anti-G suit system was engineered under contract with the Engineering Departments of the University of Colorado and the Georgia Institute of Technology. The system was delivered to the Clinical Sciences Division at Brooks AFB and assembled. It was field tested on site by contract vendor personnel from the University of Colorado and by Brooks AFB engineering staff. On-site testing found the system unsafe for human or animal use in its current configuration. The problems and proposed corrections are listed as follows.

Problem #1 - Hose connections: During the vendor's demonstration of the anti-G suit, connecting the anti-G suit to the pump through the 1.5-in. diameter hose met with extreme difficulty. The current threaded connector did not allow quick connection or disconnection between the pump and the anti-G suit abdominal bladder. It took approximately 5 minutes to screw on the hose to the connector. When the connection was broken, both bladder and pump spilled water onto the floor. To insure safety to animals and humans during emergencies, a quick disconnect system that does not flood the lab is necessary. The present configuration represents a serious safety violation.

Recommended correction: Reduce the diameter of the hose and provide a quick disconnect fitting to the hose and suit. Valves or self-sealing containers should be used to contain the fluid.

Problem #2 - Bladder inflation: Consistent filling of the pressure suit is impossible with the current design. The quantity of air trapped in the hose and bladder during filling cannot be regulated. Accurate and reproducible results are not possible with this system. During the demonstration, it was necessary to loosen the hose connection several times in order to allow water to flow into the bladder.

Recommended correction: Provide a valve on the bladder to release trapped air during the filling process.

Problem #3 - Transducer lead extraction: The anti-G suit ports for extracting transducer leads on the anti-G suit are not placed close to the dorsum of the animals to properly permit extraction of the sensor leads that are implanted on the LACR instrumented animals. The outer compression suit distributes a pressure across the surface of the animal at the point where the instrumentation leads exit. This compression will result in exit site deterioration and animal discomfort. This is a serious design flaw. Our primary goal is the humane treatment and preservation of the research animals. Ideally, suit redesign is necessary.

Recommended correction: An alternative is to implement a backpack on the animal to reduce the risk of infection and stress on the exit sites.

Problem #4 - Centrifuge capability: The current system as designed exceeds the electrical supply, mass and power limits of the centrifuge for both human and animal use. The control system interface with the hydraulic pumps through either of the slip rings cannot be tested in the current design.

Recommended correction: A system redesign is necessary to reduce size and weight. This is a fatal design flaw. The total mass on the animal side should not exceed 100 pounds. The available electrical power is 110 VAC, 60 Hz, single phase at 15 amps.

Problem #5 - Hydraulic pump hazards: The hydraulic pump does not have any safety features designed into the control system to prevent or detect the rupture of the hydraulic hose. The only safety feature present on the pump is a circuit that shuts the pump down when a sudden reversal of flow is detected. In order for this system to track at high heart rates, the vendor bypassed this safety feature. The sudden release of pressurized hydraulic fluid in a laboratory poses significant safety problems of injury to animal or human subjects or to expensive and/or sterile laboratory equipment. The current noise level exceeds the recommended levels for an office or laboratory environment. The high noise level and the high potential for altered or nonresting hemodynamic states can result in degraded test results.

Recommended correction: An in-line transducer should be placed in the hydraulic system to monitor the pressure and flow characteristics of the hydraulic fluid. The transducer should activate a safe and rapid shutdown of the hydraulic pump when unsafe conditions are identified. The hydraulic pump should be safe to operate in a stand-alone mode. The noise levels must be reduced to occupationally acceptable levels.

Problem #6 - Transducer placement: The current placement of the pressure transducer does not accurately measure the true pressure in the bladder. The transducer is currently placed at the end of the main 1.5-in. fluid pipe and is connected by a 0.25-in. pipe. Due to this connection, the transducer does not control the pressure at the bladder. What frequency response or pressure the transducer actually measures is uncertain. During the vendor demonstration, adjustments to the transducer were attempted to calibrate the system to the suit. The vendor did not have access to the anti-G suit during concept design testing. A set procedure for calibration was not available and the vendor was unable to successfully calibrate the system for the demonstration. Following the attempt at calibration, the vendor switched the system from manual to computer mode and the computer commanded the system to full pressure. As a result, the human subject wearing the anti-G suit at the time had the wind knocked out of him.

Recommended correction: The transducer position should be moved and placed on or inside the bladder for direct measurement of the pressure. Changing the transducer position will require a redesign of the bladder. Calibration procedures for the transducer must be provided.

Problem #7 - G input into the controller: The current system expects a four-bit binary input to the interface box to monitor the G-forces. Currently there is no interface provided from the centrifuge or tilt table to the system.

Recommended correction: TTL level inputs are needed for the tilt table and for the centrifuge. For the tilt table, a table angle can be used to simulate a pseudo-G magnitude. An interface to the centrifuge will have to be fabricated.

Problem #8 - Insufficient funding: The funds for the project were expended on startup costs with the off-site vendors. When the design flaws were discovered, project funds were not available to correct the deficiencies. Requests for funding from within Clinical Sciences Division resources were denied. A collaborative effort with the Laboratory of Aerospace Cardiovascular Research (LACR) was initiated to provide further funds, but there were funding cutbacks and shortfalls in the LACR budget as well.

Recommended correction: Without further funding, this project must be closed.

DISCUSSION

It is generally accepted that the anti-G suit can prevent or reduce the magnitude of both the initial and the delayed effects of positive acceleration on the cardiovascular system. The inflated anti-G suit: raises tissue pressures in the abdomen and lower extremities to prevent a large increase in vascular transmural pressures, maintains peripheral vascular resistance, reduces the pooling of blood in the capacitance vessels of the abdomen and lower extremities and increases blood return to the heart. The suit supports the abdominal wall and reduces the downward displacement of the diaphragm and secondarily the heart (G tolerance decreases with increased vertical heart/brain distances). While it is clear that the anti-G suit has a major role in pilot protection, it remains only part of the solution. The maximal protection that has been claimed for pneumatic anti-G suits is generally 2G, although experimental centrifuge studies indicate that the protection is probably closer to 1.5G[2].

The anti-G suit technology has been dramatically improved. The newest generation of anti-G suits has electronically operated bladders that can be rapidly and sequentially and differentially inflated. The Advanced Technology Anti-G Suit (ATAGS)[9] has uniform and expanded lower extremity coverage. By adding positive pressure breathing (PPB), there is a 20% increased G-endurance with unassisted 30 mmHg[14] and a 30% increase with similar assisted PPB[9] with simulated aerial combat maneuvers (SACM) at 4.5 and 7G and a two-fold increase in the 5-9G endurance SACM[15]. The Combined Advanced Technology Enhanced Design G-Ensemble (COMBAT EDGE) has incorporated positive pressure breathing (PPB)[10]. Certain well-trained individuals using the anti-G

straining maneuver for rapid onset runs (6G/sec) or a relaxed protocol during the gradual onset runs (1G/sec) with this equipment have been able to sustain consciousness for periods as long as 45-60 sec at 9G and can endure sustained 5 to 9G loads for 4-5 min[10,11].

Recent work by Moore and others[9] from the Naval Air Development Center (NADC) using a synchronized external pulsation (SEP) technique offer improved performance over that provided by the standard anti-G suit. These investigators found that when SEP of 2 psi (approximately 100 mmHg) was superimposed on the standard anti-G suit pressure, the tolerance for acceleration stress was further augmented by 0.9G above that provided by the standard pneumatic anti-G suit alone.

The modified nuclear, biologic pathogen, chemical (NBC) anti-G, anthropomorphic tank suit (ATS 2) or "Atlantis Warrior" represents the current concept for the hydrostatic anti-G suit[16]. The relaxed pilot wearing the Atlantis Warrior hydrostatic anti-G suit has been shown to be capable of sustaining 10G[13]. This suit has the added advantage of providing NBC protection to the pilot. This suit restricted movement for some of the experimental subjects and the problems of heating or cooling remain to be addressed. While the Atlantis Warrior demonstrates improved pilot performance and protection, many problems remained unsolved.

Unlike these technologies, the fluid-filled ECG-triggered anti-G suit remains to be proven. The challenges of size, weight, complexity, pilot comfort, and acceptance are enormously challenging. In many respects, this system has been eclipsed by the progress these investigators have made with the pneumatic anti-G suit.

CONCLUSIONS

The potential of a fluid-filled ECG-triggered anti-G suit remains unrealized due its complexity, to current limitations in technology, and to funding constraints. While the availability of flexible and nondistensible fabrics for anti-G suit overgarments make effective hydrostatic anti-G suits possible, the technology for synchronized external pulsation coupled to hydrostatic anti-G suits is not mature enough to master the complexity of this system. The size and weight of the current system exceeds the structural load maximums on the Armstrong Laboratory centrifuge. The weight and complexity of a fluid-filled anti-G suit currently preclude its use on the centrifuge and in flight. If evolving technology permits a size and weight reduction of the pressure delivery systems without sacrificing $+G_z$ tolerance, this fluid-filled ECG-triggered anti-G suit proposal can be reexamined. Until then, the project will remained shelved.

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